Validation of the polyvoids in the design of bituminous mixtures with coal tar as a binder

Validación del polígono de vacíos en el diseño de mezclas bituminosas con alquitrán de hulla como ligante

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Abstract

The world has developed different methodologies for the design of asphalt mixtures; each of which is intended to optimise and find the optimal combination of materials that allow them to be resistant under specific travel, climate and structural support conditions. This article presents the results of an investigation which utilised coal tar as a binding agent for road surface mixtures and carried out a comparison of results of the physical and mechanical properties of sample bituminous mixtures produced by two distinct methodologies, Marshall and Ramcodes. Finally, an analysis was carried out on the suitability of tar as a binding agent and on utilising the Ramcodes methodology when designing mixtures.

Keywords: Coal tar, Marshall, Ramcodes, bituminous mixture

Resumen

En el mundo se han desarrollado diferentes metodologías para el diseño de mezclas asfálticas; cada una procura optimizar y encontrar la combinación óptima de materiales que permita ser resistente bajo unas condiciones determinadas de tránsito, clima y apoyo estructural. En este artículo se muestran los resultados de una investigación donde se utilizó el alquitrán de hulla como ligante en mezclas para pavimentos y se realiza una comparación de los resultados de las propiedades físicas y mecánicas de probetas con mezcla bituminosa elaboradas por dos metodologías distintas, la Marshall y la Ramcodes. Por último, se realiza el análisis de la conveniencia de utilizar el alquitrán como ligante y de utilizar la metodología Ramcodes para el diseño de mezclas.

Palabras clave: Alquitrán de hulla, Marshall, Ramcodes, mezcla bituminosa

1. Introduction

Since the beginning of time, man has endeavoured to develop activities to allow survival and evolution. In principle, these activities were limited to the direct consumption of resources that nature provided, with the improvement of industrial activities increasing the presence of residues that were no longer bearable for the natural environment.

Road construction is an activity that implies a significant consumption of natural resources, during which the production of bituminous mixtures involves using great quantities of aggregate and asphalt; the majority of these coming from quarrying and oil exploitation. Taking into account the politics of sustainability, this investigation aims to contribute towards the development in the use of by-products in the iron and steel industry.

Furthermore, with comparisons to the Marshall methodology, this investigation aims to analyse the benefits of using the Ramcodes methodology in the design of bituminous mixtures and which out of these is most used in our environment.

In order to verify previous findings, with help from the SPSS programme, statistical analysis was performed with the results obtained by the two methodologies, to determine whether these results differ and whether the use of this methodology is advisable.

2. Materials used

2.1 Tar as a binding agent

Tar, as shown in Figure 1, is a semi-solid or liquid bituminous product that is obtained as a residue of distillation, in the absence of air, organic substances that contain volatile materials such as coal or wood. It is a cold binding agent, resistant to water, insoluble in lubricating oils and petroleum fuels, soluble in ether, benzene, carbon disulphide, chloroform and quinoline. The tar consists of

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aliphatic and naphthenic components containing hydrogen, oxygen, nitrogen and sulphur.

The tar utilised in this study is produced in a Coking plant of the iron and steel company Acerías Paz del Río S.A.,

whose carried out the process at 1000°C (Gómez, 2002). Table 1 shows the physicochemical properties of this material.

Figure 1. Tar produced by Acerías Paz del Río S.A

Table 1. Physicochemical properties of tar. Source: Departamento Laboratorio Acerías Paz del Río

Parameter	Unit	Average
Humidity	%	7
Ashes	%	0.10
Insoluble in Quinoline	%	4
Insoluble in Toluene	%	3
Calorific value	kcal/kg	8900

2.2 Aggregate

The materials utilised in a bituminous mixture must be subjected to rigorous studies to establish the possibility of their use. For this, since coarse aggregate uses a crushed type of gravel, this was subjected to the following tests: erosion in the Los Angeles abrasion testing machine, percentage of fractures, extension rate and flattening rate.

In addition, tests were carried out to determine the specific gravity and the percentage of absorption. As fine aggregate used sand and, as a filler mineral, it used Portland cement and grains of sand passed through sieve #200, their specific gravities were determined. All the tests were made taking into account the testing standards for road materials set by INVÍAS and ASTM.

The type of mixture selected whilst carrying out this study was a dense mixture in type 19 heat (MDC-19) in accordance with Article 450-13, of the general road construction specifications by INVÍAS (2013a).

3. Methodology

The methodology used in the development of this investigation was considered in three stages: the first was

conducting tests in order to know the characteristics of the materials used in the design of the bituminous mixtures; the second stage regards carrying out necessary tests to obtain the working formula of the bituminous mixture for the Marshall methodology modified by University of Illinois, and for the Ramcodes methodology, and the third, with regard to the comparison of the results from both methodologies and the analysis in the advantage of using tar as a binding agent and the implementation of the Ramcodes methodology.

3.1 Marshall Method

The purpose of this method is to determine the optimum binding content for a specific aggregate mixture and to provide information on the physical and mechanical properties of hot bituminous mixture, so that it is possible to establish if they meet the parameters of densities and optimal content vacuum during the construction of the pavement layer.

The overall objective of the design process involves determining a combination and economic intensity of aggregate and binding agents that produce a mixture with: sufficient binding agent to guarantee a durable pavement; adequate stability to meet traffic demands without causing any deformation or displacement; a vacuum content high enough to allow a slight amount of additional compaction under heavy, without any bleeding or loss of stability and

enough workability to allow for efficient placement without segregation (Hosseinzadeh et al., 2016).

3.2 Ramcodes Method

The Ramcodes method (Ochoa-Díaz, 2013; Sánchez et al., 2002), an acronym for RAtional Methodology for COMpacted geomaterial's DEnsification and Strength analysis developed by F.J. Sánchez-Leal, is a methodology based on factorial experiments and the practical experience in design and control, for an analysis of densification and compacted geomaterial resistance.

The Marshall accelerated by Ramcodes is an application developed for the quick design of traditional Marshall procedure, which rationally binds the design specifications with the field control criteria, by implementing the "polyvoids" which defines an area which meets all vacuum specifications (VAM, VAF y VA) (Sánchez-Leal et al., 2011). These vacuums are based according to the binding content (%CA) and Bulk density (G_{mb}) and are indicated on maps as isolines, for the allowed values, the intersection of these lines produce a graphic construction of space %CA – G_{mb} , which results in a polygon, in which, through its centroid, is mathematically possible to obtain an asphalt content that meets all vacuum specifications for the mixture (Delgado et al., 2006).

The following steps have been proposed to modify or accelerate the original Marshall design process (Sánchez-Leal, 2009):

- Determine the specific effective gravity (G_{se}), the specific Bulk gravity of a combination of aggregates (G_{sb}) and the apparent specific gravity (G_{sa}) of the combination of selected

aggregates. Verify that $G_{sa} > G_{se} > G_{sb}$, according to theoretical definitions.

- Mathematically obtain, from the polyvoids, the optimum binding content, considering the specifications and specific gravities of the combination of aggregates.
- Following Marshall test regulations, mix the combination of aggregates with the optimum binding content and condense three specimens to determine the vacuums and try them to determine their stability and flow. Work out the average of the results.
- Verify if the average of the binding content and the Bulk density enters into the polyvoids. If not, then the attempt failed. Select another combination of aggregates and return to the first step.
- Verify if the average of stability and flow of the specimens comply with the specification. If not, then the attempt failed. Select another combination of aggregates and return to the first step.

4. Experimental design

In Table 2, six granulometric distributions of the material use are shown, with their respective dosages (Sánchez-Leal, 2007); the particle sizes were adjusted so that, in a strip of the MDC-19 mixture, they were exactly in the centre, on the thin side and on the thick side of this strip, Figure 2, in order to evaluate the impact of the particle size in the mixture's performance.

Figure 2. The Granulometric Distribution of the Mixtures

The variable is the type of mineral filler (cement or sand), adjusted to the granulometric strip of the mixture. The laboratory testing process for the Marshall and Ramcodes methodologies was developed in two stages.

In the first stage, six Marshall designs were carried out for experimental development, three with cement as a filler and three with sand passed through sieve #200. The heating

temperate of the aggregates and the binding agent was 40°C with a constant compaction of 75 shocks per side (traffic level NT-2) (INVIAS, 2013b), making a factorial experiment varying in two factors, the binding content variable by 0.5% for each mixture and variable gradation according to the position on the granulometric strip. The former, with the objective of finding the working formula for the Marshall design, followed by the compaction process and outcomes of the mechanical performance of the mixtures.

In the second part, six Ramcodes were developed (identical particle sizes to those used with Marshall), with constant binding percentages for each particle size, with a constant compaction of 75 shocks per side and a mixing temperature of 40°C. These percentages were obtained according to the use of the RAMSOFT program based on the Ramcodes methodology, which generated the work formula (optimum binding percentage) for each mixture, followed by

the compaction process and outcomes of the mixtures stability and flow. Once the samples were compressed, they were left to cool for 15 minutes, before removing the mould. Once out of the mould, they were allowed to cool and cure at room temperature for eight days, so that the mixtures solvents evaporated. Following this, the test was continued to determine the stability and flow in the Marshall plan.

Table 2. Mixture particle distributions and aggregate type

Mixture	Aggregate	Material	Percentage	Distribution
M-1	Coarse	Gravel	41	The fine side of the granulometric strip
	Fine	Sand	52	
	Filler	Cement	7	
M-2	Coarse	Gravel	46	Centre of the granulometric strip
	Fine	Sand	49	
	Filler	Cement	5	
M-3	Coarse	Gravel	50	The coarse side of the granulometric strip
	Fine	Sand	46	
	Filler	Cement	4	
M-4	Coarse	Gravel	40	The fine side of the granulometric strip
	Fine	Sand	54	
	Filler	Sand passing #200	6	
M-5	Coarse	Gravel	44	Centre of the granulometric strip
	Fine	Sand	51	
	Filler	Sand passing #200	5	
M-6	Coarse	Gravel	47	The coarse side of the granulometric strip
	Fine	Sand	49	
	Filler	Sand passing #200	4	

4.1 Results of the tests carried out with both methodologies

The following Table 3 and Table 4 present the results obtained from the mixtures designed through both methodologies.

Regarding the obtained results and taking into account the specifications of Table 450.4 from article 450-07 of the general specifications of the construction of highways, the mixtures prepared with Portland cement as a filler achieve a

level of transit NT-1; However, the flow is above the range of 2-4mm.

In the observed results of the mixtures prepared with sand passing the sieve #200 as a filler, some parameters achieve the specifications for a level of transit NT-1, although the flow resulted remotely from the specified range. The results of the Marshall Method for the Mixture M-2 fulfil all the specifications for the level of transit NT-2, to which this work is the formula that best presents mechanical behaviour.

Table 3. Results of the Designed Mixtures with Cement as a Filler

Designed mixtures with gravel, sand, and cement							
Parameter	M-1		M-2		M-3		Request NT-2
	Marshall	Ramcodes	Marshall	Ramcodes	Marshall	Ramcodes	
Bitumen (%)	7.40	7.13	6.50	6.87	6.42	6.63	-
Gmb (gr/cm ³)	2.13	2.14	2.14	2.13	2.13	2.13	-
Stability (Kg)	734	793	792	755	668	688	>750
Flow (mm)	4.13	4.03	3.88	4.13	4.26	4.22	2 - 4
Vv (%)	4.0	3.86	4.0	3.88	4.0	3.88	3 - 5
VAM (%)	16.37	15.78	15.22	15.80	15.53	15.81	> 15
VFA (%)	75.70	75.51	73.90	75.43	74.30	75.43	65 - 78

Table 4. Results of the Designed Mixtures with Sand as a Filler

Designed mixtures with gravel, sand, and sand passing sieve #200							
Parámetro	M-4		M-5		M-6		Request NT-2
	Marshall	Ramcodes	Marshall	Ramcodes	Marshall	Ramcodes	
Bitumen (%)	6.60	6.80	6.60	6.70	6.20	6.70	-
Gmb (gr/cm ³)	2.18	2.18	2.17	2.17	2.18	2.17	-
Stability (Kg)	527	472	702	643	665	588	>750
Flow (mm)	8.0	10.1	9.2	10.0	8.6	9.8	2 - 4
Vv (%)	4.0	3.9	4.0	3.9	4.0	3.9	3 - 5
VAM (%)	15.6	15.8	15.8	15.8	15.0	15.8	> 15
VFA (%)	73.7	75.5	74.0	75.5	73.0	75.5	65 - 78

4.2 Sensibility Analysis for Mixture M-2

For this mixture, the study of sensibility was achieved based on statistical techniques of the analysis of factorial experiments according to Ramcodes. Furthermore, the behaviour of the two most influential factors in the bituminous mixtures (G_{mb} y $\%P_b$) was studied. This analysis has great advantages in controlling the compact mixtures.

Besides the vacant requisites, the bituminous mixture has to achieve the mechanical property's requirements such as stability and flow. The graphic representation of the response values under G_{mb} and $\%P_b$ generate a contour plot

that is an image of the response surface for each selected mechanical parameter.

Ramcodes are based on a two-level factorial experiment—the binding content ($\%P_b$) and the specific bulk weight (G_{mb}). The usage of maps permits a vision of variation of the mechanical properties inside the area where the space specifications are achieved. In Figure 3, the behaviour of stability is shown, while in Figure 4, the behaviour of flow is demonstrated. This mixture has high or low performance depending on where status is established.

Figure 3. Behaviour of Stability

Figure 4. Behaviour of Flow

4.3 Statistical Analysis

In order to do the comparison of stability in relation to the used methodologies, the box diagram, Figure 5, is initially verified. It shows a small difference between the values of stability and the variability of similar data.

In order to confirm if a significant difference exists between the results of stability for the two methodologies, it is necessary to verify the assumption of normality, for which the results of the test of normality are shown in Table 5.

In a diagram or graph Q-Q Normal, every value observed (Y_i) is compared to the typical score NZ_i that theoretically corresponded to that value in the normal standardised distribution. On the X-axis, the values observed are represented and ordered from least to greatest (stability and flow); in such an order, the typical, normal scores are represented (NZ_i). When a sample precedes a normal

population, the corresponding points for each part are clustered around the diagonal represented in the diagram. The diversions in the diagonal indicate deviations in normality.

Figure 6 shows the diagram Q-Q Normal for the data established and obtained by the Marshall Method. Figure 7 presents the diagram Q-Q Normal for the data established and obtained by RAMCODES method. The above information verifies that the normal distribution adequately traces the data of stability by methodology.

Furthermore, the Shapiro-Wilk Test in Table 5 confirms this behaviour at a level of confidence of 95% ($\alpha=0.05$)

Marshall Method: $p\text{-value} = 0.532 > 0.05$

RAMCODES Method: $p\text{-value} = 0.101 > 0.05$

Figure 5. Box Diagram regarding Stability

Table 5. Normality Test Results

	Method	Kolmogorov-smirnov ^a			Shapiro-wilk		
		Statistical	Gf	Sig.	Statistical	Gf	Sig.
Stability	Ramcodes	0.228	15	0.034	0.902	15	0.101
	Marshall	0.144	15	0.200*	0.950	15	0.532

a. Correction of the significance of Lilliefors

*. This is an inferior limit of true significance

With this information, the statistical inference developed relating the difference in the average value of stability for both methodologies. The results obtained in the SPSS software for this test is presented in Table 6.

With the assumption of equal variances, these results lead to the conclusion that no significant difference exists in the values of stability ($p\text{-value} = 0.856 > 0.05$). This implies that the use of any method does not generate a significant difference in the values of stability.

To compare the flow in respect to the two applied methodologies, the box diagram in Figure 8 is initially verified. Figure 8 shows a similar behaviour for the data of flow for both methodologies.

Using the Mann-Whitney Test (Table 7) for the independents samples, that which is observed in Figure 8 can be confirmed.

Regarding the confidence level of 95%, $p\text{-value} = 0.299 > 0.05$, no significant difference between the values of flow can be concluded by using either methodologies.

Figure 6. Diagram Q-Q Normal, Stability regarding the Marshall Method

Figure 7. Diagram Q-Q Normal, Stability regarding the Ramcodes Method

Table 6. Test Results of Independent Samples regarding Stability

		Levene's test Equal Variances		Test t for the equality of the median						
		F	Sig.	t	gl	Sig. (bilateral)	Dif. in median	Tip. Error	95% confidence interval	
									Inferior	Superior
STB.	Equal Variances	0.018	0.894	-0.183	28	0.856	-9.133	49.978	-111.508	93.242
	Different Variances			-0.183		0.856	-9.133	49.978	-111.544	93.277

Figure 8. Box Diagram regarding Flow

Table 7. Results of the Mann-Whitney Test

Statistics of Contrast ^b	
	Flow
U for Mann-Whitney	87.500
W for Wilcoxon	207.500
Z	-1.039
Asymptotic Sig. (bilateral)	0.299
Exact Sig. [2*(unilateral Sig.)]	0.305 ^a

a. No corrections for the ties.

b. Group Variable: Method

5. Conclusions

It is not intended to replace asphalt for pavement in the preparation of mixtures. Instead, the intention is to seek alternatives that permit the selection of product that adjust to the needs of every specific project.

Ramcodes is a methodology of great usefulness for its design, production and quality control of bituminous mixtures, provided that it guarantees the compliance of the volumetric parameters demanded by the specifications. Furthermore, there exists various benefits to using this methodology as it saves times, resources and money. Thankfully, it is only necessary to make three briquettes in comparison to 15 briquettes in the Marshall Method.

Amongst the inconsistent observations in the development of this investigation and keeping the statistical analysis in mind, it was demonstrated that no significant difference exists between the results obtained by the Marshall

Method and the Ramcodes Method—being that the usage of the Ramcodes Method is valid in the design of the bituminous mixtures of pavements.

The mixture that best presents the behaviour and best adjusts to the required technical requests by INVIAS norms was the preparation with gravel as a course aggregate, sand as a fine aggregate, and cement as a filler. However, one must continue with this investigation in order to find the best way to utilise this bind and thereby contribute to the environment.

Given the thermal susceptibility of bitumen and, therefore, of the asphalt mix, it is determined that this type of mixture can be used in cold to temperate climates. Under these conditions, the behaviour of the mixture will be acceptable under the action of burdens imposed by traffic.

If some mixtures did not fulfil the INVIAS requirements for the wearing layer of the roadway, it would be possible to use them as enhanced base or sub-base layers.

To guarantee an acceptable behaviour of this type of mixture requires a strict control of quality in the minimum

requirements of the aggregates just like the usage of cement as a filler. This quality control must be done in each phase of the project: in the design, development of the mixture, curing

time, transportation to the work site, placement and compaction of the mixture.

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